NUCLEAR DATA AND MEASUREMENTS SERIES

ANL/NDM-94

Evaluated Neutronic Data File for Yttrium

by

A.B. Smith, D.L. Smith, P. Rousset, R.D. Lawson, and R.J. Howerton

January 1986

ARGONNE NATIONAL LABORATORY,
ARGONNE, ILLINOIS 60439, U.S.A.

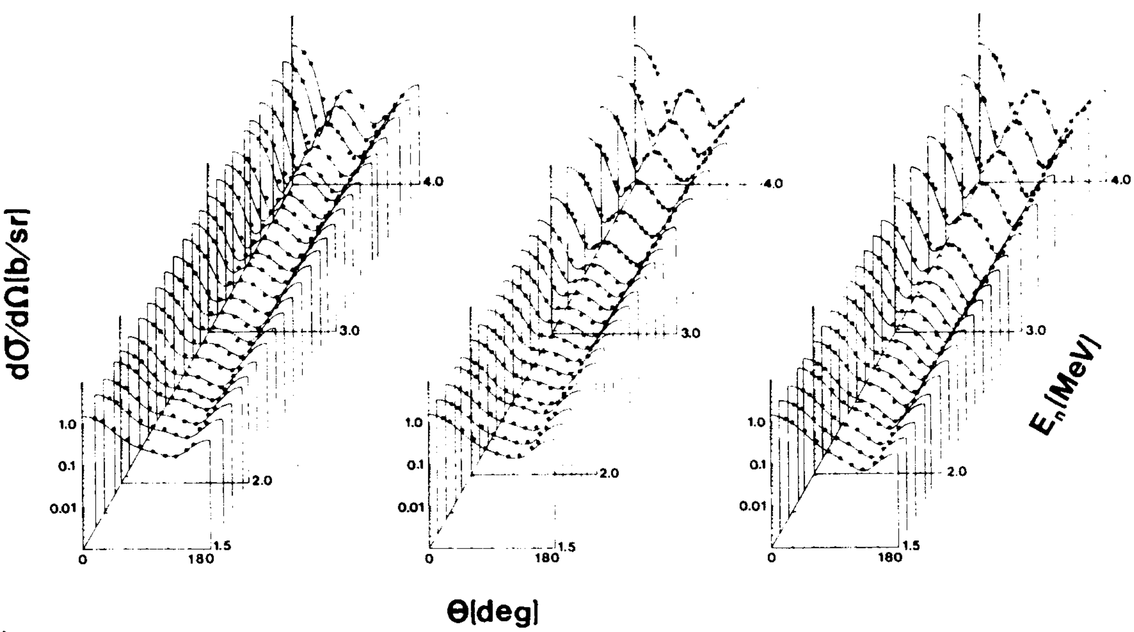
NUCLEAR DATA AND MEASUREMENTS SERIES

ANL/NDM-94

EVALUATED NEUTRONIC DATA FILE FOR YTTRIUM

by
A. B. Smith, D. L. Smith, P. Rousset and R. D. Lawson,
Argonne National Laboratory
and
R. J. Howerton
Lawrence Livermore National Laboratory

January 1986



ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Operated by THE UNIVERSITY OF CHICAGO
for the U. S. DEPARTMENT OF ENERGY
under Contract W-31-109-Eng-38

ANL/NDM-94

EVALUATED NEUTRONIC DATA FILE FOR YTTRIUM*

by

A. B. Smith, D. L. Smith, P. Rousset and R. D. Lawson,
Argonne National Laboratory
and

R. J. Howerton
Lawrence Livermore National Laboratory

January 1986

Keywords:

Evaluated neutronic data file, Yttrium, Thermal to 20 MeV.

Applied Physics Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439
USA

* This work supported by the U. S. Department of Energy.

NUCLEAR DATA AND MEASUREMENTS SERIES

The Nuclear Data and Measurements Series presents results of studies in the field of microscopic nuclear data. The primary objective is the dissemination of information in the comprehensive form required for nuclear technology applications. This Series is devoted to: a) measured microscopic nuclear parameters, b) experimental techniques and facilities employed in measurements, c) the analysis, correlation and interpretation of nuclear data, and d) the evaluation of nuclear data. Contributions to this Series are reviewed to assure technical competence and, unless otherwise stated, the contents can be formally referenced. This Series does not supplant formal journal publication but it does provide the more extensive information required for technological applications (e.g., tabulated numerical data) in a timely manner.

INFORMATION ABOUT OTHER ISSUES IN THE ANL/NDM SERIES:

A list of titles and authors for reports ANL/NDM-1 through ANL/NDM-50 can be obtained by referring to any report of this series numbered ANL/NDM-51 through ANL/NDM-76. Requests for a complete list of titles or for copies of previous reports should be directed to:

Section Secretary
Applied Nuclear Physics Section
Applied Physics Division
Building 316
Argonne National Laboratory
9700 South Cass Avenue
Argonne, Illinois 60439
USA

ANL/NDM-51 Measured and Evaluated Neutron Cross Sections of Elemental Bismuth by A. Smith, P. Guenther, D. Smith and J. Whalen, April 1980.

ANL/NDM-52 Neutron Total and Scattering Cross Sections of ^{6}Li in the Few MeV Region by P. Guenther, A. Smith and J. Whalen, February 1980.

ANL/NDM-53 Neutron Source Investigations in Support of the Cross Section Program at the Argonne Fast-Neutron Generator by James W. Meadows and Donald L. Smith, May 1980.

ANL/NDM-54 The Nonelastic-Scattering Cross Sections of Elemental Nickel by A. B. Smith, P. T. Guenther and J. F. Whalen, June 1980.

ANL/NDM-55 Thermal Neutron Calibration of a Tritium Extraction Facility using the ^{6}Li(n,t)^{4}He/^{197}Au(n,γ)^{198}Au Cross Section Ratio for Standardization by M. M. Bretscher and D. L. Smith, August 1980.

ANL/NDM-56 Fast-Neutron Interactions with ^{182}W, ^{184}W and ^{186}W by P. T. Guenther, A. B. Smith and J. F. Whalen, December 1980.

ANL/NDM-57 The Total, Elastic- and Inelastic-Scattering Fast-Neutron Cross Sections of Natural Chromium by Peter T. Guenther, Alan B. Smith and James F. Whalen, January 1981.

ANL/NDM-58 Review of Measurement Techniques for the Neutron Capture Process by W. P. Poenitz, August 1981.

ANL/NDM-59 Review of the Importance of the Neutron Capture Process in Fission Reactors by Wolfgang P. Poenitz, July 1981.

ANL/NDM-60 Gamma-Ray Detector Calibration Methods Utilized in the Argonne FNG Group Activation Cross Section Measurement Program by James W. Meadows and Donald L. Smith, April 1984.

ANL/NDM-61 Fast-neutron Total and Scattering Cross Sections of ^{58}Ni by Carl Budtz-Jørgensen, Peter T. Guenther, Alan B. Smith and James F. Whalen, September 1981.

ANL/NDM-62 Covariance Matrices and Applications to the Field of Nuclear Data by Donald L. Smith, November 1981.

ANL/NDM-63 On Neutron Inelastic-Scattering Cross Sections of ^{232}Th, ^{233}U, ^{235}U, ^{238}U, ^{239}U, and ^{239}Pu and ^{240}Pu by Alan B. Smith and Peter T. Guenther, January 1982.

ANL/NDM-64 The Fission-Fragment Angular Distributions and Total Kinetic Energies for ^{235}U(n,f) from 0.18 to 8.83 MeV by James W. Meadows and Carl Budtz-Jørgensen, January 1982.

ANL/NDM-65 Note on the Elastic Scattering of Several-MeV Neutrons from Elemental Calcium by Alan B. Smith and Peter T. Guenther, March 1982.

ANL/NDM-66 Fast-neutron Scattering Cross Sections of Elemental Silver by Alan B. Smith and Peter T. Guenther, May 1982.

ANL/NDM-67 Non-evaluation Applications for Covariance Matrices by Donald L. Smith, July 1982.

ANL/NDM-68 Fast-neutron Total and Scattering Cross Sections of ^{103}Rh by Alan B. Smith, Peter T. Guenther and James F. Whalen, July 1982.

ANL/NDM-69 Fast-neutron Scattering Cross Sections of Elemental Zirconium by Alan B. Smith and Peter T. Guenther, December 1982.

ANL/NDM-70 Fast-neutron Total and Scattering Cross Sections of Niobium by Alan B. Smith, Peter T. Guenther and James F. Whalen, July 1982.

ANL/NDM-71 Fast-neutron Total and Scattering Cross Sections of Elemental Palladium by Alan B. Smith, Peter T. Guenther and James F. Whalen, June 1982.

ANL/NDM-72 Fast-neutron Scattering from Elemental Cadmium by Alan B. Smith and Peter T. Guenther, July 1982.

ANL/NDM-73 Fast-neutron Elastic-Scattering Cross Sections of Elemental Tin by C. Budtz-Jørgensen, Peter T. Guenther and Alan B. Smith, July 1982.

ANL/NDM-74 Evaluation of the ^{238}U Neutron Total Cross Section by Wolfgang Poenitz, Alan B. Smith and Robert Howerton, December 1982.

ANL/NDM-75 Neutron Total and Scattering Cross Sections of Elemental Antimony by A. B. Smith, P. T. Guenther and J. F. Whalen, September 1982.

ANL/NDM-76 Scattering of Fast-Neutrons from Elemental Molybdenum by Alan B. Smith and Peter T. Guenther, November 1982.

ANL/NDM-77 A Least-Squares Method for Deriving Reaction Differential Cross Section Information from Measurements Performed in Diverse Neutron Fields by Donald L. Smith, November 1982.

ANL/NDM-78 Fast-Neutron Total and Elastic-Scattering Cross Sections of Elemental Indium by A. B. Smith, P. T. Guenther, and J. F. Whalen, November 1982.

ANL/NDM-79 Few-MeV Neutrons Incident on Yttrium by C. Budtz-Jørgensen, P. Guenther, A. Smith and J. Whalen, June 1983.

ANL/NDM-80 Neutron Total Cross Section Measurements in the Energy Region from 47 keV to 20 MeV by W. P. Poenitz and J. F. Whalen, July 1983.

ANL/NDM-81 Covariances for Neutron Cross Sections Calculated Using a Regional Model Based on Elemental-Model Fits to Experimental Data by D. L. Smith and P. T. Guenther, November 1983.

ANL/NDM-82 Reaction Differential Cross Sections from the Least-Squares Unfolding of Ratio Data Measured in Diverse Neutron Fields by D. L. Smith, January 1984.

ANL/NDM-83 The Fission Cross Sections of Some Thorium, Uranium, Neptunium and Plutonium Isotopes Relative to ^{235}U by J. W. Meadows, October 1983.

ANL/NDM-84 ^{235}U and ^{239}Pu Sample-Mass Determinations and Intercomparisons by W. P. Poenitz and J. W. Meadows, November 1983.

ANL/NDM-85 Measurement of the $^{51}V(n,p)^{51}Ti$ Reaction Cross Section from Threshold to 9.3 MeV by the Activation Method by D. L. Smith, J. W. Meadows and I. Kanno, June 1984.

ANL/NDM-86 Energy-Differential Cross Section Measurement for the $^{51}V(n,\alpha)^{48}Sc$ Reaction by I. Kanno, J. W. Meadows, and D. L. Smith, July 1984.

ANL/NDM-87 Cross-Section Measurement for the $^{7}Li(n,n't)^{4}He$ Reaction at 14.74 MeV by D. L. Smith, J. W. Meadows, M. M. Bretscher and S. A. Cox, September 1984.

ANL/NDM-88 An Evaluated Nuclear Data File for Niobium by A. B. Smith, D. L. Smith and R. J. Howerton, March 1985.

ANL/NDM-89 Compilation and Evaluation of 14-MeV Neutron Activation Cross Sections for Nuclear Technology Applications: Set I by Bernard P. Evain, Donald L. Smith and Paul Lucchese, April 1985.

ANL/NDM-90 Fast-Neutron-Spectrum Measurements for the Thick-Target $^{9}Be(d,n)^{10}B$ Reaction at $E_d = 7$ MeV by D. L. Smith, J. W. Meadows and P. T. Guenther, April, 1985.

ANL/NDM-91 On The Energy-Dependence of the Optical-Model of Neutron Scattering from Niobium by A. B. Smith, P. T. Guenther and R. D. Lawson, May 1985.

ANL/NDM-92 Nuclear Data Uncertainties (Vol.-I): Basic Concepts of Probability by Donald L. Smith, April 1986.

ANL/NDM-93 Integral Cross-Section Measurements for $^{7}Li(n,n't)^{4}He$, $^{27}A\ell(n,p)^{27}Mg$, $^{27}A\ell(n,\alpha)^{24}Na$, $^{58}Ni(n,p)^{58}Co$ and $^{60}Ni(n,p)^{60}Co$ Relative to ^{238}U Neutron Fission in the Thick-Target $^{9}Be(d,n)^{10}B$ Spectrum At $E_d = 7$ MeV by D. L. Smith, J. W. Meadows and M. M. Bretscher, October 1985.

TABLE OF CONTENTS

ANL/NDM-94

EVALUATED NEUTRONIC DATA FILE FOR YTTRIUM*

by

A. B. Smith, D. L. Smith, P. Rousset+ and R. D. Lawson,
Argonne National Laboratory
and
R. J. Howerton, Lawrence Livermore National Laboratory

ABSTRACT

A comprehensive evaluated neutronic data file for yttrium is presented and documented. The file extends from thermal neutron energies to 20 MeV, and includes all reactions necessary for comprehensive neutronic calculations. The input data base, the requisite theoretical calculations, the evaluation methods and results, and outstanding problem areas, are described. Attention is given to quantitative uncertainty specification and to energy conservation among various reaction products and the photon-production data. The file is presented in the ENDF-format system, and has been transmitted to the National Nuclear Data Center, Brookhaven National Laboratory.

* This work supported by the U. S. Department of Energy.
+ Permanent address, University of Grenoble, France.

I. Introduction

This document describes the formulation and contents of a comprehensive evaluated nuclear data file for yttrium. The experimental data base is discussed in some detail. The methods of evaluation, including quantitative uncertainty definition, are outlined. Although there are no integral experiments against which the data can be checked, energy-conservation verification is described. The evaluated quantities are graphically presented and compared with previous evaluations. The corresponding numerical values are available from the National Nuclear Data Center, Brookhaven National Laboratory. The file is entirely in the ENDF system of formats and should be fully consistent with processing codes designed to use such evaluated-data formulations. The objective is a comprehensive evaluated file for neutronic calculations and the contents are comprehensive in that context. Certain applications may require additional information (e.g., activity information) that should be obtained from the respective specialized file systems (1).

Elemental yttrium is monoisotopic (^{89}Y) and magic in neutron number (N=50). It lies at the end of a prominent fission-product decay chain with chain yields varying from approximately 6% for Th-232 fission to 1.2% for Pu-240 fission. As such, its neutronic properties are a consideration in the optimization of FBR and similar nuclear-energy systems. The neutron interaction with ^{89}Y is of significant basic interest from a number of points of view (2,3). Recent measurement programs have greatly augmented the experimental knowledge of the neutron interaction with this nucleus (4,5), and the consequence is a potential for considerable improvement of the evaluated data file for applications and for enhanced understanding of the basic neutron-nucleus interaction. This document addresses the first of these opportunities.

II. Resonance properties

This evaluation uses the resonance parameter representation up to an incident neutron energy of 150 keV. The resonance parameters were explicitly taken from the compilation of Mughabghab et al. (6). The bound resonance of this compilation was deleted and, alternatively, the behavior of the cross sections as thermal energies are approached was obtained by introducing a small energy-average background in the neutron-scattering and radiative-capture files in such a manner as to assure the correct thermal-cross-section values. At the upper-energy limit of the resonance representation, this background was also adjusted to smoothly join the resonance cross sections onto the energy-averaged cross sections. The matching was accomplished using 20 keV averages of the cross sections generated from the resonance parameters. The neutron scattering and radiative-capture cross sections implied by the resonance representation are illustrated in Fig. 1. These cross section were constructed from the resonance parameters using the code RECENT (7). The uncertainties associated with the resonance parameters are very complex and the reader is referred to ref. 6 for guidance in this area.

III. Energy-averaged total cross sections

The evaluated energy-averaged total cross sections, extending from the resonance parameters to 20.0 MeV, were entirely deduced from experimental values. The experimental data base, consisting of the works of refs. 5 and 8-18, was assembled from the literature, as referenced in CINDA, and the files of the National Nuclear Data Center. The numerical values were initially inspected using large-scale plots. It was clearly evident that a few of the data sets were grossly inconsistent with the body of the information, and these were abandoned. Very few of the data sets specified both systematic and statistical uncertainties. Most sets cited only statistical uncertainties, and a few gave no uncertainties of any type. A rigorous evaluation requires knowledge of both systematic and statistical uncertainties. Where these were not specified they were estimated using subjective judgments based upon the available documentation and a familiarity with the various experimental techniques involved. At low energies (e.g., less than 600 keV) there are large fluctuations observed in the measurements, reflecting partially-resolved underlying resonance structure. In this region, self-shielding is a concern, ignored in most of the measurements. Where possible, self-shielding corrections were made. Where small corrections were not possible, systematic uncertainties were increased. The low-energy fluctuations were smoothed and the data base reduced to manageable proportions by averaging the experimental values of each data set over 50-keV intervals below 1.0 MeV, and over 100 keV intervals at higher energies. The averaging correctly propagated the uncertainties of the individual datum values. The resulting averaged data base is illustrated in Fig. 2A. It is reasonably consistent and comprehensive.

The evaluated cross sections were deduced from the above experimental data using the rigorous statistical method of Poenitz (19). That method, implemented with the code GMA, provides the evaluated data, their uncertainties, and the associated correlation matrix. The evaluated results fluctuated slightly with energy, reflecting the character of the underlying data. These fluctuations were smoothed by fitting the evaluated data set with a simple optical model, concurrently varying the ten parameters: real and imaginary strengths (with a quadratic energy dependence of each), radii and diffusenesses. The resulting model parameters provided an excellent description of the experimentally-based evaluated data, and were remarkably consistent with the physical interpre-

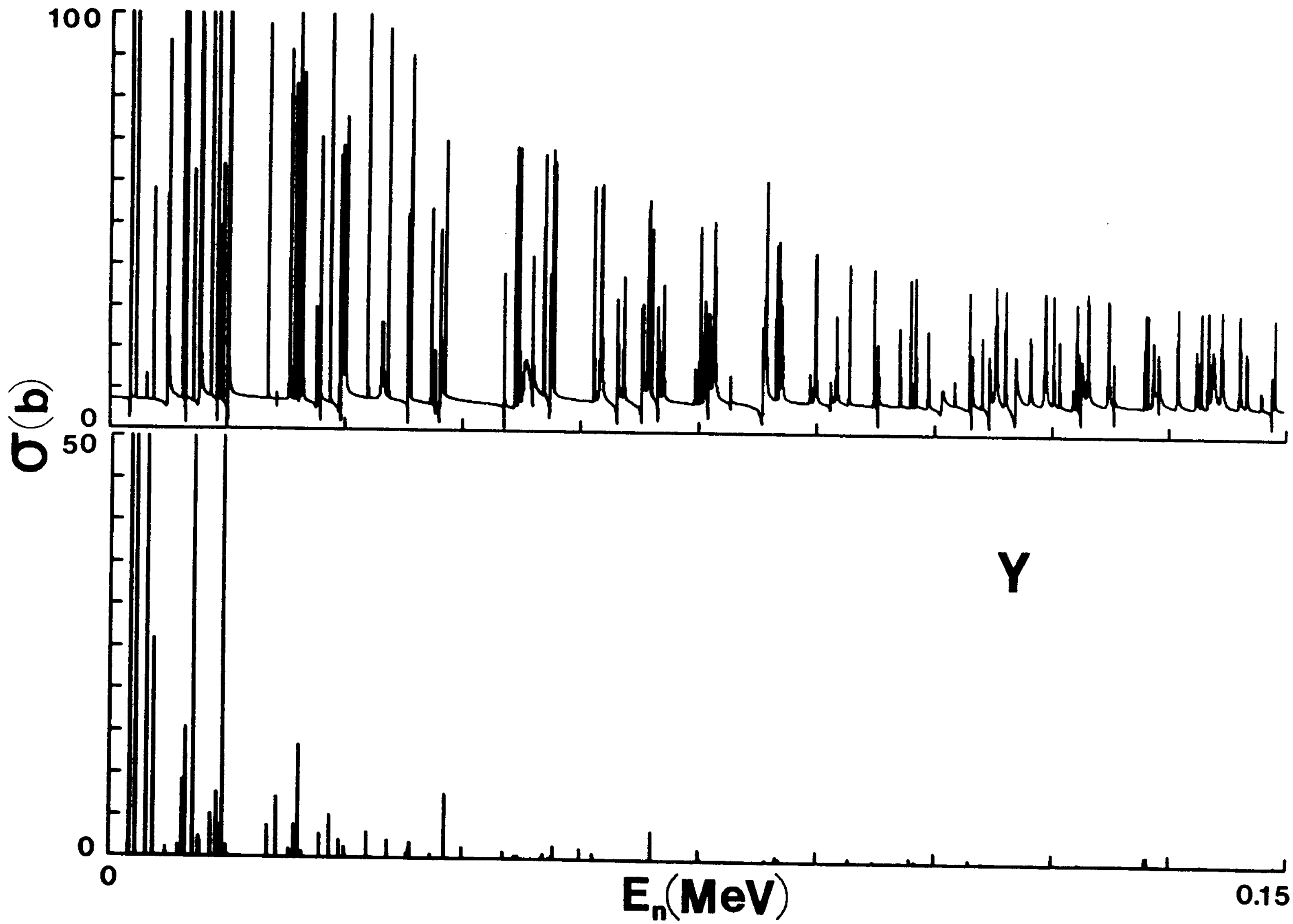


Fig. 1. Neutron scattering (upper) and radiative-capture (lower) cross sections constructed from the evaluated resonance parameters.

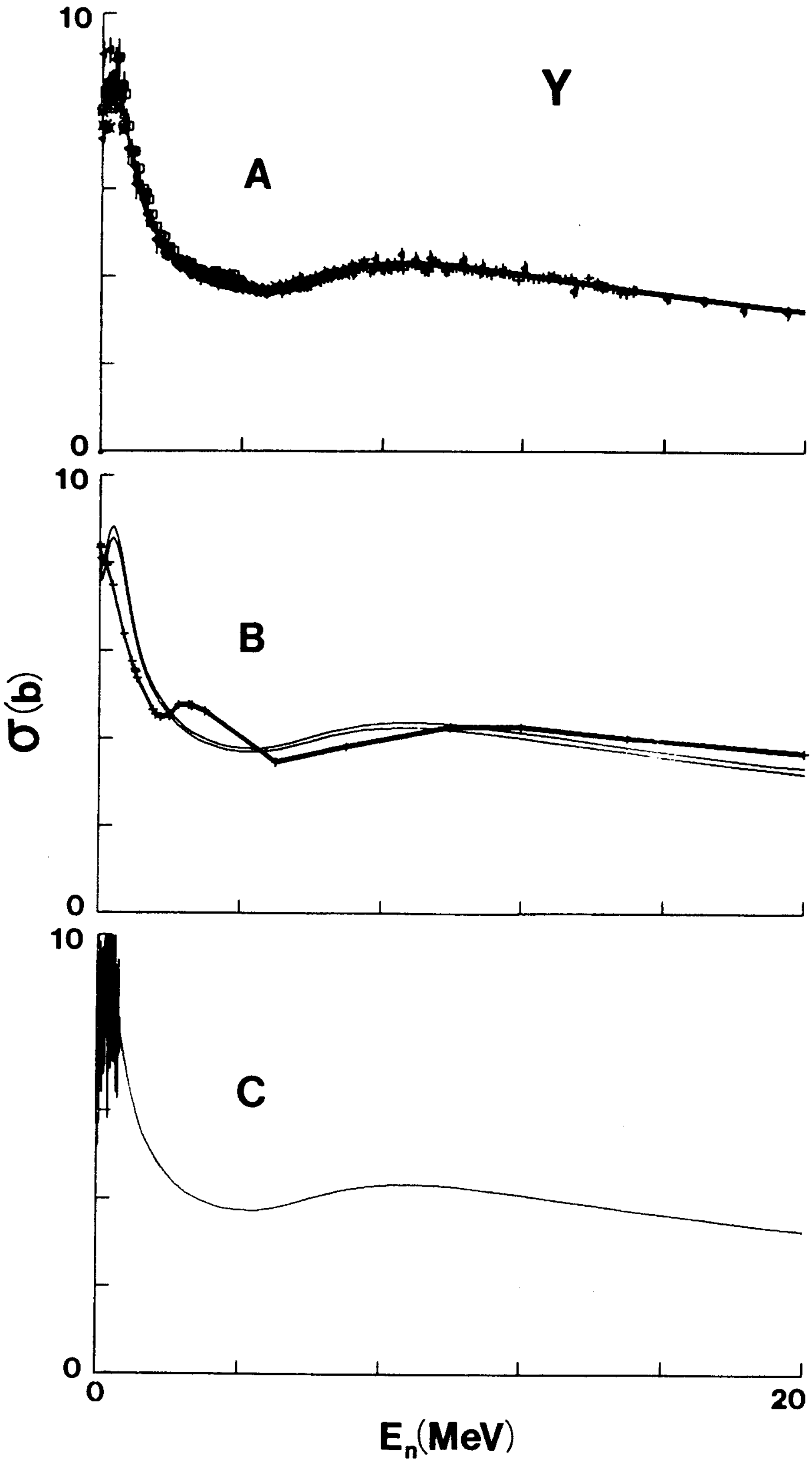


Fig. 2. Evaluated energy-averaged neutron total cross sections of yttrium. A=experimental data base (symbols) and present evaluation (curve). B=uncertainty limits of present evaluation (light curves) and the ENDF/B-V evaluation (heavy curve). C=present evaluation with low-energy fluctuations.

tations of ref. 3. The uncertainties associated with the evaluation ranged from 1.0% to a maximum of 2.1%. This uncertainty spread is illustrated in Fig. 2B. These uncertainties indicate that the energy-averaged yttrium neutron total cross section is very well-known from approximately 100 keV to 20.0 MeV.

The preceding is an energy-averaged evaluation, describing general energy trends. Below approximately 600 keV, several measurements (e.g., refs. 8 and 14) clearly show large and partially resolved resonance structures. These were incorporated in the evaluation by normalizing the fluctuating values to the energy-averaged evaluation, with the result shown in Fig. 2C. This representation preserves the energy-averaged behavior while giving some indication of the large fluctuations. This result should not be confused with a fully-resolved resonance representation. Since the file must be internally consistent, this structure will appear elsewhere in the evaluation. No partial cross sections have been determined with equivalent resolutions, thus it was decided to propagate the total-cross-section structure into the elastic-scattering cross section alone. In the present case that approximation is reasonably valid as the only other partial cross section in this energy region is due to radiative capture and it is very small.

The present evaluated neutron total cross sections are qualitatively very different from those given in ENDF/B-V, as illustrated in Fig. 2B. There are magnitude differences of 10% to 20% over much of the energy range. The relative shape of the ENDF/B-V evaluation seems inconsistent with any known physical interpretation.

IV. Energy-averaged elastic-scattering cross sections

From 1 to 10 MeV the evaluated elastic-scattering cross sections are largely based upon the experimental values of refs. 3, 4, 5 and 20, primarily the former three (supported by references cited therein). This data base gives energy detail and accuracies of 3-4%. Below approximately 1.0 MeV, the elastic-scattering cross sections are essentially equivalent to the total cross sections, with only a small difference due to radiative capture. Above 10.0 MeV the cross sections were extrapolated to 20.0 MeV using the model of ref. 3. That extrapolation is supported by the ability of the model to describe the above evaluated total cross sections to 20.0 MeV to within better than several percent. The estimated uncertainties in the evaluated elastic-scattering cross sections are: i) 2-3% below 1.0 MeV, ii) 2-4% from 1.0 to 10.0 MeV, and iii) approximately 4% from 10.0 to 20.0 MeV. These are relatively small uncertainties. The evaluated elastic-scattering cross sections, and the above total cross sections, imply the non-elastic cross section shown in Fig. 3. These non-elastic values, in turn, define the envelope of the remaining partial cross sections, some of which are not well-known.

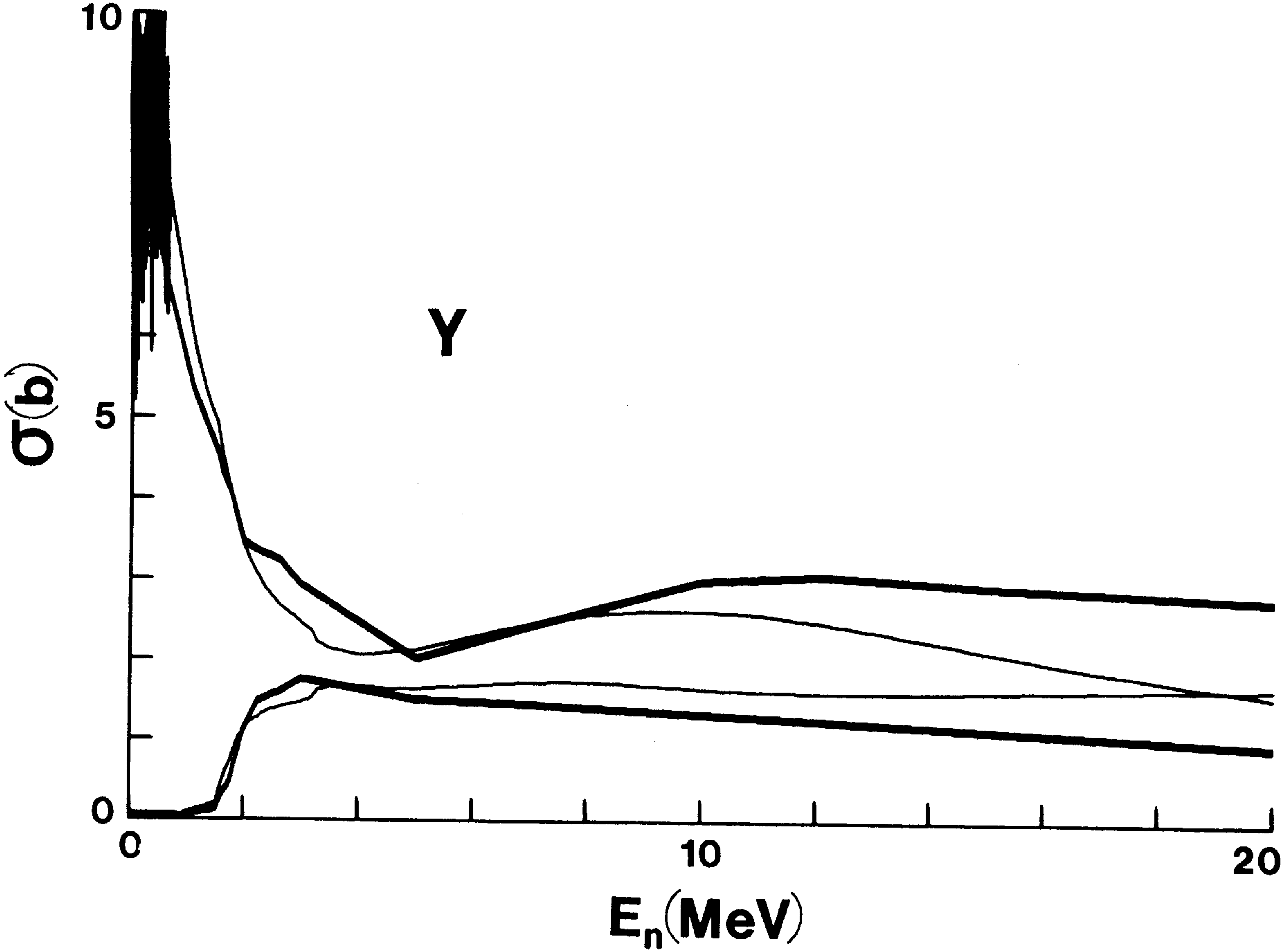


Fig. 3. Comparison of evaluated elastic- and nonelastic-scattering cross sections. The light curves indicate the present evaluations and the heavy curves those of ENDF/B-V.

The elastically-scattered neutron angular distributions were taken from the experimental values and the model of refs. 3-5 and 20 (and references cited therein). The general trends are illustrated in Fig. 4. Throughout, "Wick's limit" was satisfied. Some of the basic physical implications of these distributions are discussed in ref. 3.

The present evaluated elastic-scattering cross sections are compared with those of ENDF/B-V in Fig. 3. There are some very large differences, and these will impact on other aspects of either evaluation. Certain characteristics of the ENDF/B-V formulation seem unphysical. It is not realistic to compare differential elastic-scattering values, as ENDF/B-V assumes isotropic elastic scattering to 20.0 MeV.

V. Discrete inelastic-scattering cross sections

The present evaluated discrete-inelastic-scattering cross sections extend up to excitation energies of 3.2 MeV, assuming the energies, spins, and parities given in refs. 4 and 5. The corresponding inelastic cross sections were largely based upon the experimental results of refs. 4, 5 and 20, supported by the ancillary experimental evidence of refs. 21-23. This data base is relatively consistent, as shown in Fig. 5, an exception being some of the values of ref. 21. The latter were abandoned although no source of the discrepancy could be identified by their author. The measurements consist of both (n,n') and (n;n',gamma) results. The former were given emphasis in the determination of the cross section normalizations, as the experimental interpretations are unambiguous, and the latter were used to define the cross sections near threshold and to resolve the detailed level structure, as the (n;n',gamma) method can provide superior energy resolution and results that are generally easy to interpret near threshold. The experimental results were interpolated using the statistical model and the optical potential of refs. 3 and 5. The agreement between measured and calculated values was very good (as illustrated in Fig. 5), and thus the calculations were used for the evaluation. The angular distributions of the discrete-inelastic-neutron groups were assumed to be isotropic. The measurements support this assumption in the lower energy region where the cross sections are of significant size and where the statistical process is the dominant reaction mechanism. At higher energies (above 4-5 MeV), the inelastic-neutron emission can be significantly anisotropic (see ref. 20), but the corresponding cross sections have generally fallen to the order of a mb. The reader interested in detailed anisotropies is directed to the measurements and calculations of refs. 5 and 20.

The uncertainties associated with the preceding evaluated quantities vary from approximately 5%, for the prominent excitations, to 10-20+% for levels which are very weakly excited. Generally, these uncertainties increase with energy and decreasing cross-section magnitudes.

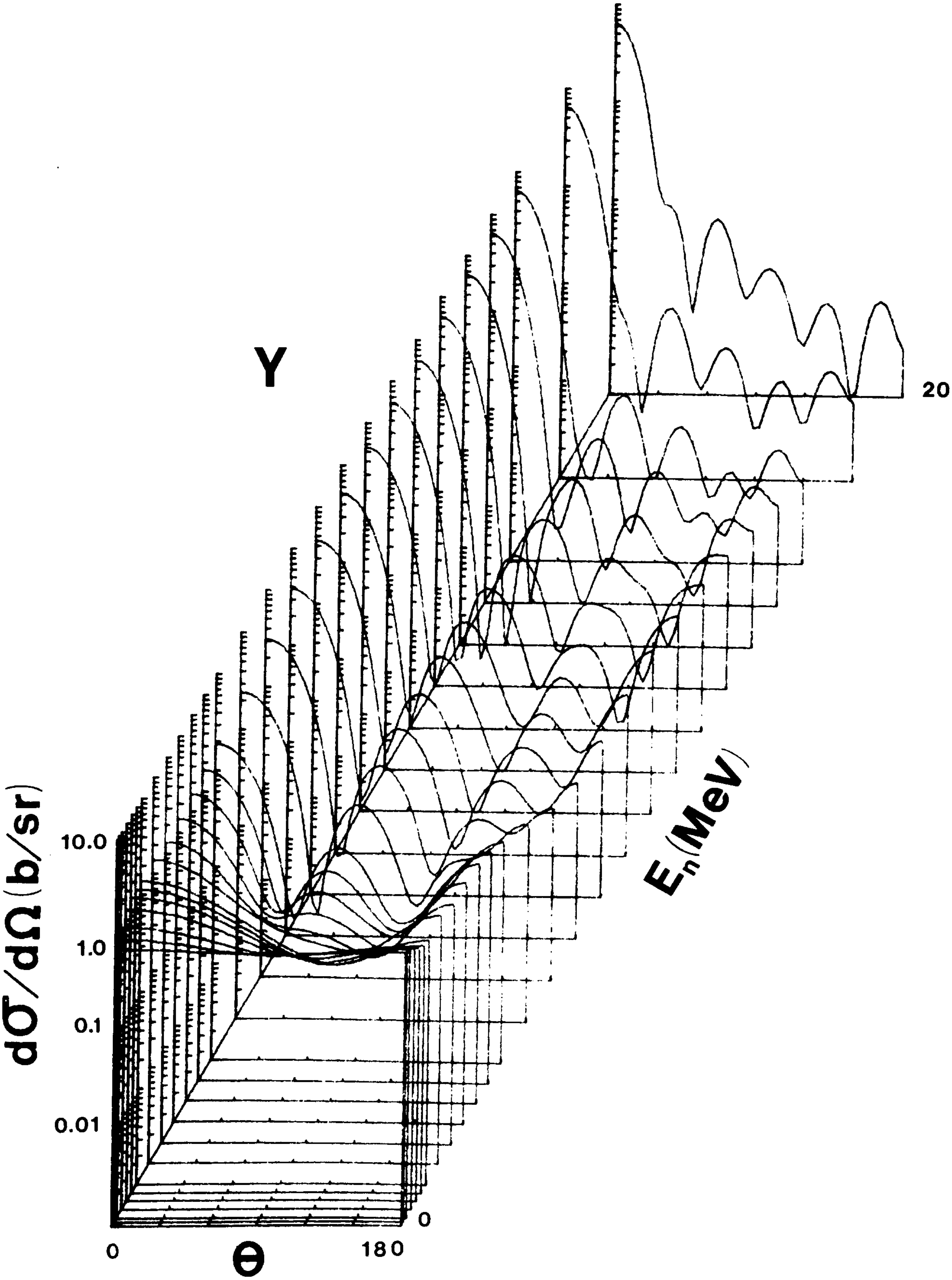


Fig. 4. Evaluated differential-elastic-scattering cross sections (in center-of-mass system).

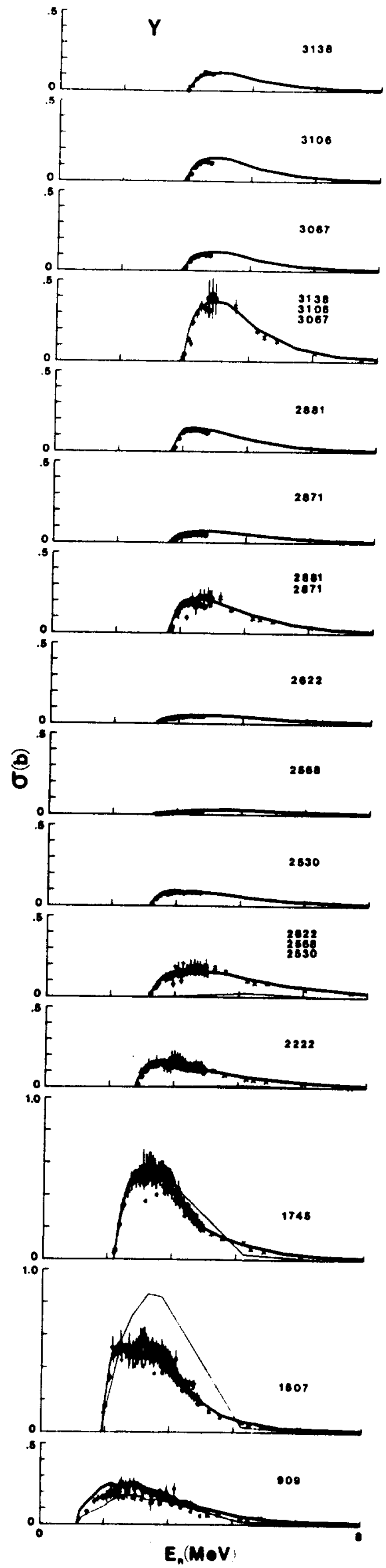


Fig. 5. Comparison of measured (symbols) and evaluated discrete-inelastic-scattering cross sections. The heavy curves indicate the present evaluation and the light curves that of ENDF/B-V.

Comparisons of the present evaluated discrete-inelastic-scattering cross sections with those of ENDF/B-V are possible for only the first few levels given in the latter file. For some of these levels the two evaluations are in reasonable agreement, for others there are large discrepancies (e.g., ENDF/B-V is nearly a factor of two larger for some of the prominent excitations). These comparisons are illustrated in Fig. 5.

VI. Continuum-inelastic scattering

The continuum-inelastic cross section (CI) is implied by the above total cross section and the other partial cross sections. There are no direct and comprehensive measurements of it. For the present evaluation, the CI is defined as the difference between the evaluated nonelastic cross section and the sum of the other partial cross sections. This method insures internal file consistency. The CI extends from the highest-energy level used in the discrete-inelastic evaluation (approximately 3.2 MeV) to 20 MeV. The energy dependence and magnitude of the CI, together with those of other related cross sections, are shown in Fig. 6. Without any adjustments, the behavior is consistent with physical expectations. At lower energies the major contribution is due to statistical-inelastic processes. Channel competition rapidly dilutes these above the (n,2n') threshold, and the cross section falls to a relatively energy-constant value determined by the pre-compound processes. The magnitude of the pre-compound component is qualitatively consistent with the predictions of Weisskopf-Ewing calculations carried out using the ALICE computer code of Blann (24). The uncertainties associated with the CI evaluated cross sections are approximately 10% up to 12 MeV, and somewhat larger at higher energies.

The statistical component of the CI is expected to result in essentially isotropic neutron emission, while the pre-compound component follows a complex energy-angle correlation (24). The primary motivation of the present evaluation is the provision of a file for fission-product neutronic calculations. These are not sensitive to the high-energy pre-compound component. Moreover, at the present time the commonly used FBR, etc., processing and calculational codes do not accept the pre-compound angle-energy correlations. ENDF/B-VI formats make provision for such correlations, but the exact formulation and the various options remain a matter of some debate at this writing. Given these considerations, the present evaluation accepts the approximations of the ENDF/B-VI files 4 and 5. This compromise should not have any significant effect on the use of the file in the anticipated application areas (e.g., assessment of fission-product effects). Given the above rationale, the CI neutron emission was assumed to be isotropic. Compound and pre-compound components of the emission spectrum were approximated using the two-temperature distribution of the form $\phi = E * (A * \exp(-E/T1) + B * \exp(-E/T2))$, where A (T1) and B (T2) represent compound and pre-compound contributions, respectively. Below the (n,2n') threshold, the four constants can be reasonably evaluated from the measurements of refs. 20

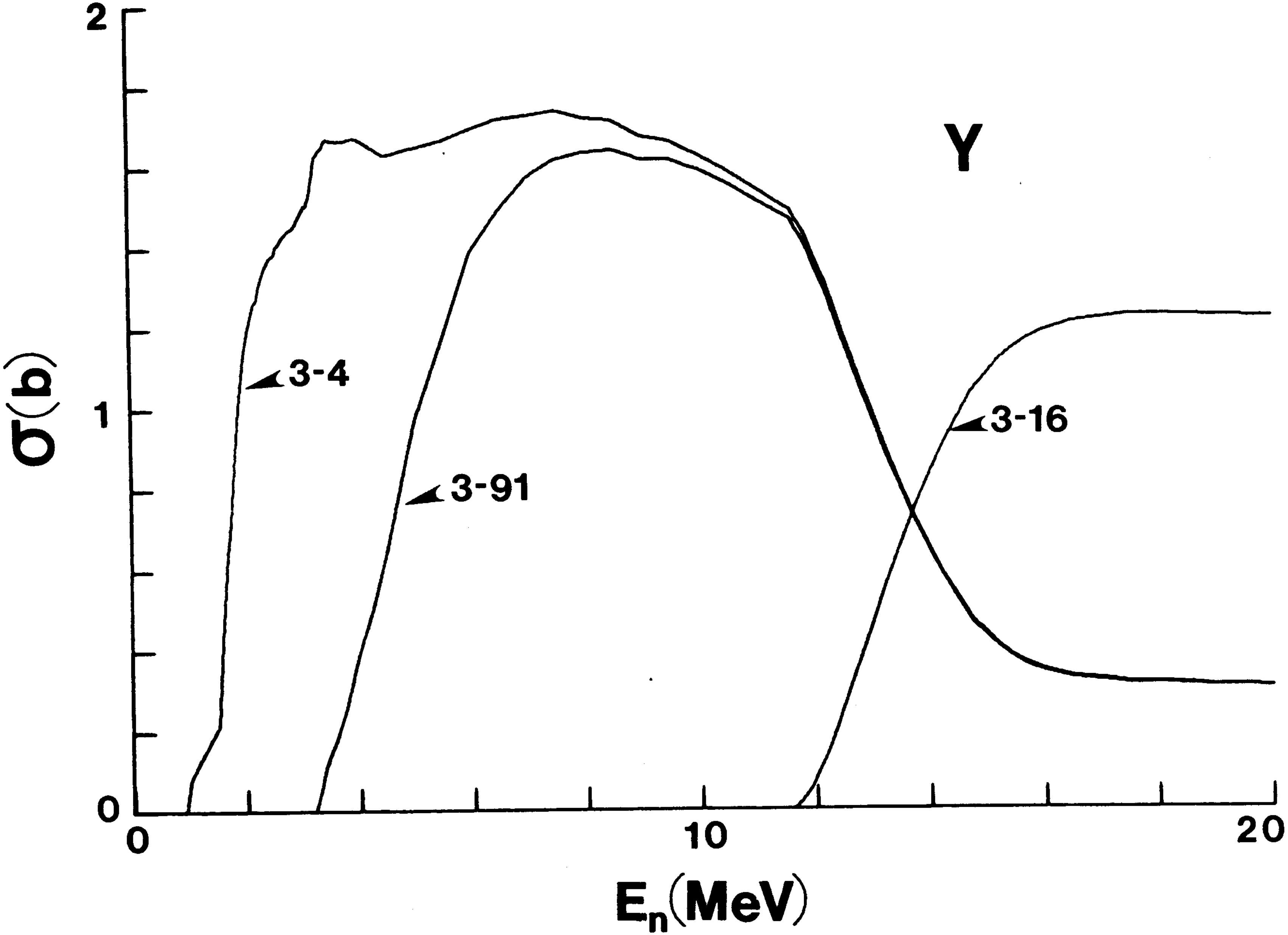


Fig. 6. Comparison of evaluated total-inelastic (3-4), continuum inelastic (3-91) and (n,2n') (3-16) cross sections.

and 25. The temperatures (T) take the forms T1 = 0.1 + 0.0455 * E and T2 = 0.3 + 0.37 * E. At higher energies, calculations (24) and the CI evaluated cross sections guide the choice of A and B, with T1 and T2 retaining the above energy dependencies. The result is a pragmatic approximation of the physical reality, consistent with the general concepts of compound and pre-compound emission, and with the practical aspects of near-term utilization of the file.

VII. (n,2n') and (n,3n') processes

The threshold for the (n,3n') reaction is above the 20.0 MeV limit of the present evaluation and thus the reaction can be ignored. The threshold for the (n,2n') reaction is at 11.469 MeV. The respective evaluation is founded entirely upon an experimental data base derived from CINDA and the files of the National Nuclear Data Center. It consists of the work of references 26-49. The majority of these measured values were obtained using activation techniques, and four sets involve prompt-neutron-detection techniques (refs. 46-49). The entire data base is shown in Fig. 7A. An inspection of this figure clearly suggests that a minority of the measurements are inconsistent with the body of the information. These were rejected to obtain the data base of Fig. 7B, which was used for the evaluation. Where readily possible, the experimental data were corrected to contemporary reference standards, decay properties, etc. The evaluation was subjectively constructed through the data of Fig. 7B, with the results indicated by the curves. Estimated uncertainties are:

Threshold to 12.0 MeV	±25%
13.5 MeV	±10%
15.0 MeV	± 5%
18.0 MeV	± 5%
20.0 MeV	± 6%

with linear interpolation between the cited values. These estimates are likely to be very conservative, as suggested by the curves of Fig. 7B. Very few of the data points fall outside the uncertainty band, and none of the individual uncertainties fail to reach the band. Furthermore, the results obtained using the two different methods (activation and prompt detection) are generally consistent. This evidence leads to the conclusion that the (n,2n') cross section of yttrium is well-known. It is impossible to make any comparisons with ENDF/B-V as the latter file does not contain the reaction. The present evaluation agrees with that of Philis (50) to well within the respective uncertainties.

There are apparently no observations of the emitted spectra of (n,2n') neutrons. The evaluation assumes a primarily statistical and isotropic neutron emission, represented by $\phi = E * \exp(-E/T)$. The

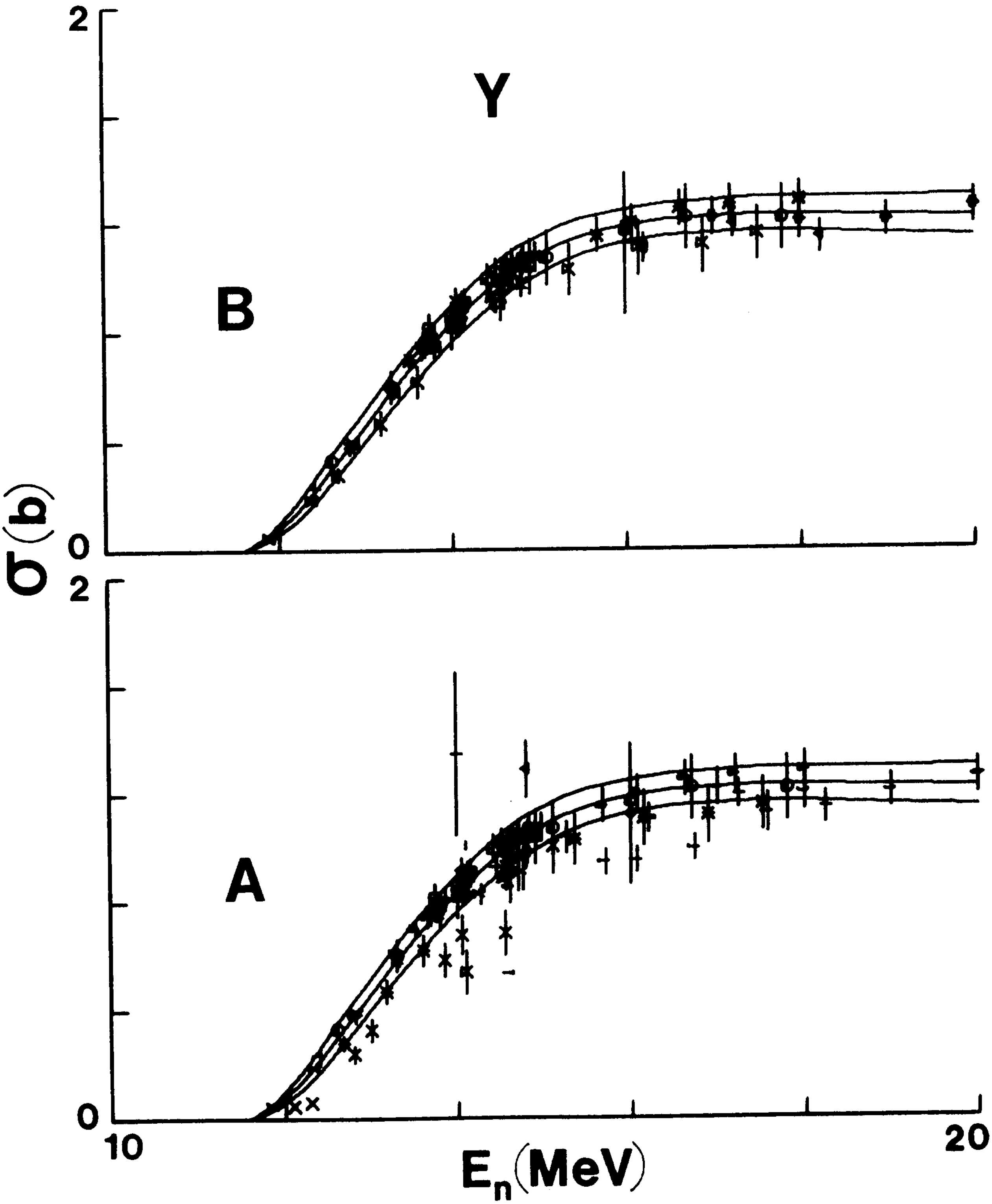


Fig. 7. Measured and evaluated (n,2n') cross sections of yttrium. A=entire data base (symbols). B=selected data base (symbols). Curves denote the evaluation, ± the uncertainty.

temperature was taken to be 0.7 MeV at 15 MeV incident energy, and to have an energy dependence of 120 keV/MeV. The emission spectra are presented as point-wise distributions. This simple representation is relatively consistent with calculational estimates (24). Moreover, the (n,2n') threshold is at too high an energy to make the process of significance in most fission-product assessments.

VIII. Radiative-capture cross sections

The experimental data base shown in Fig. 8 (refs. 51-68), assembled from the literature (CINDA referenced) and the files of the National Nuclear Data Center, is not particularly definitive. The older measurements generally used activation techniques and gave results characteristically larger than the values obtained in the more recent measurements using prompt-detection methods. In addition, below several-hundred keV, the cross-section fluctuations, very evident in the preceding total cross sections, make it difficult to determine the energy-averaged behavior. At the same time, the available information is not detailed enough to make possible a definitive resonance representation above approximately 150 keV. The evaluation primarily relies upon the recent prompt-detection data of refs. 51, 66 and 68. Refs. 51 and 68 are in good agreement and cover the range of approximately 0.5-3.0 MeV, a region where fluctuations are not a particular concern. The data of ref. 66 are average values of partially resolved resonances, binned into 10 keV intervals. There are large fluctuations, but the general trend is relatively consistent with the higher-energy data. The evaluation interpolates between the measured quantities using a compound-nucleus calculation. That calculation, using the computer code ABAREX (69), adjusts the s-wave strength function to optimize the description of the results of refs. 51, 66 and 68. The resulting strength function was within 10% of that deduced from the analysis of low-energy resonance data (6). In addition, a small direct-capture component was calculated at very high energies, consistent with experimental observation (e.g., ref. 67). That direct-capture component is largely a cosmetic effect from the point of view of most applications as the corresponding cross sections are generally less than 1 mb. The resulting evaluation is compared with the data base and with the ENDF-V evaluation in Fig. 8. The uncertainties are approximately: 18% for 0.01-0.1 MeV, 14% for 0.1-0.5 MeV, 10% for 0.5-3.0 MeV, 15% 3.0-5.0 MeV, and 20% at higher energies. The ENDF/B-V evaluation is approximately a factor of two larger than that of the present work, and inconsistent with all recent experimental results.

IX. Charged-particle-emission processes

IX-1. (n,p) and (n;n',p) reactions

There are quantitative experimental data for the (n,p) cross section

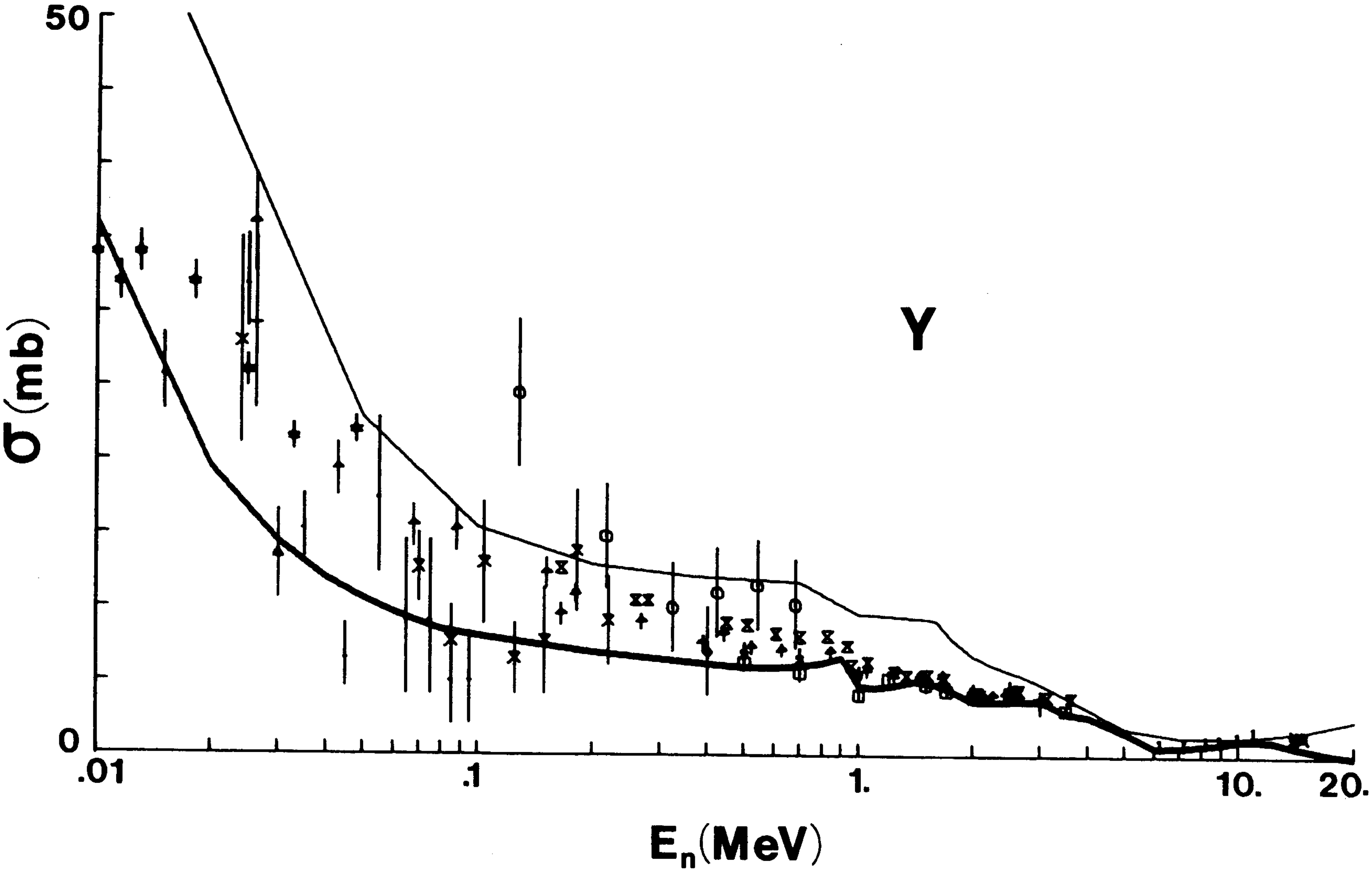
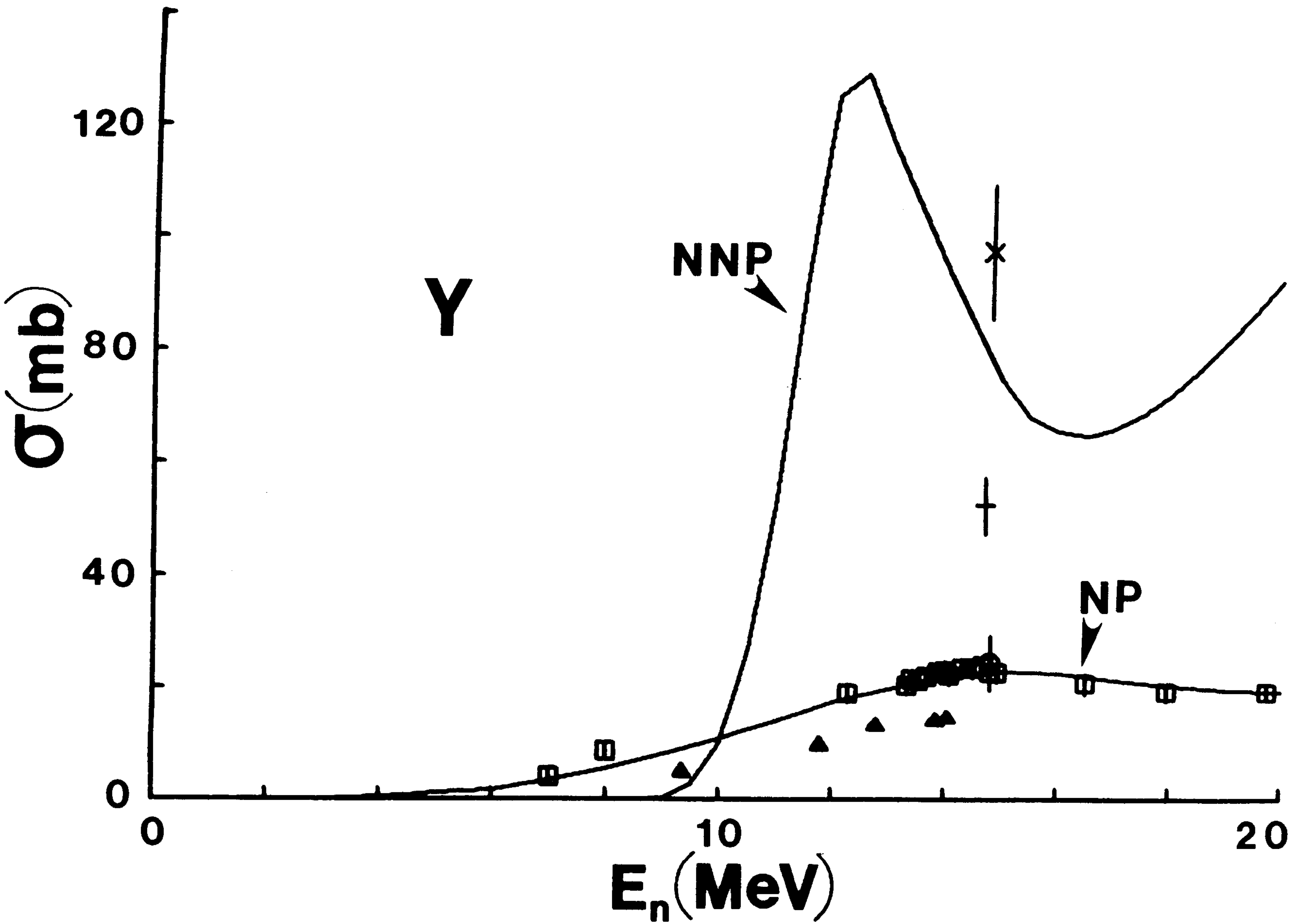


Fig. 8. Comparison of experimental capture data base (symbols), the present evaluation (heavy curve) and the evaluation of ENDF/B-V (light curve). These are energy-averaged quantities. The present evaluation employs resonance parameters up to 150 keV, as described in the text.

(70-73), notably those of ref. 70. In addition, there is a recently-reported cross section for total hydrogen production at an incident energy of approximately 15 MeV (74). The relative energy dependence of the (n,p) cross section has been estimated by Arthur using multiple-step Hauser-Feshbach theory (75). That prediction is consistent with the available experimental evidence and with calculational estimates based upon the models of refs. 24 and 76. Therefore, the (n,p) cross section given by Arthur was taken for the evaluation with no renormalization. Excepting the total hydrogen-production result of ref. 74, there is no experimental neutron evidence for the (n;n',p) cross section. Model estimates indicate that the process is energetically-favored (24, 75, 76), and that respective cross sections larger than those for the (n,p) process can be expected at higher energies. This indication is supported by the total hydrogen-production result (74), and by consideration of the $^{91}Zr(t,alpha)^{90}Y$ reaction, as discussed by Arthur. The present evaluation assumes that the experimental total hydrogen-production results obtained near 15 MeV by Haight et al. (74) and the relative energy dependence predicted by Arthur are representative of the (n;n',p) process. With these assumptions, the predictions of ref. 75 were multiplied by 1.47 to obtain the present evaluation. The experimental data and the present evaluations are shown in Fig. 9. The uncertainties that are associated with the evaluated results are relatively large, approximately 20+% for the (n,p) cross sections and 30+% for the (n;n',p). The neutron spectrum emitted from the (n;n',p) process was assumed to be statistical in nature, and thus is represented by a simple temperature model with T=0.96 MeV at 14 MeV, with a linear energy dependence. ENDF/B-V has no comparable cross sections.

IX-2. (n,alpha) and (n;n',alpha) processes

The respective experimental data base (refs. 70, 71, 72, 74, and 77-80) is very limited, contradictory, covers a relatively narrow energy range, and is confined to the (n,alpha) reaction, as illustrated in Fig. 10. It is apparent that the (n;n',alpha) cross sections are relatively the much smaller of the two, and thus the total helium production cross sections of ref. 74 is a reasonable check of the (n,alpha) cross section. Given this weak experimental foundation, considerable reliance must be placed upon theoretical extrapolation. Arthur has calculated the respective cross sections using a cascade Hauser-Feshbach formulation (75), and his results are reasonably consistent with those obtained using a similar computational code written by Wilmore (76). Thus the present evaluation relies upon the Arthur-calculated values to obtain the energy dependent cross-section shapes and the relative intensities of the (n,alpha) and (n;n',alpha) cross sections. The calculations were renormalized (upward by 30%) to bring them into good agreement with the recent helium-production results of Haight et al. (74). The two evaluated results are illustrated in Fig. 10. For most applied purposes, the



18

Fig. 9. Measured and evaluated (n,p) and (n;n',p) cross sections. Experimental (n,p) results are indicated by data symbols, where "X" refers to total hydrogen production, and curves indicate the present evaluations.

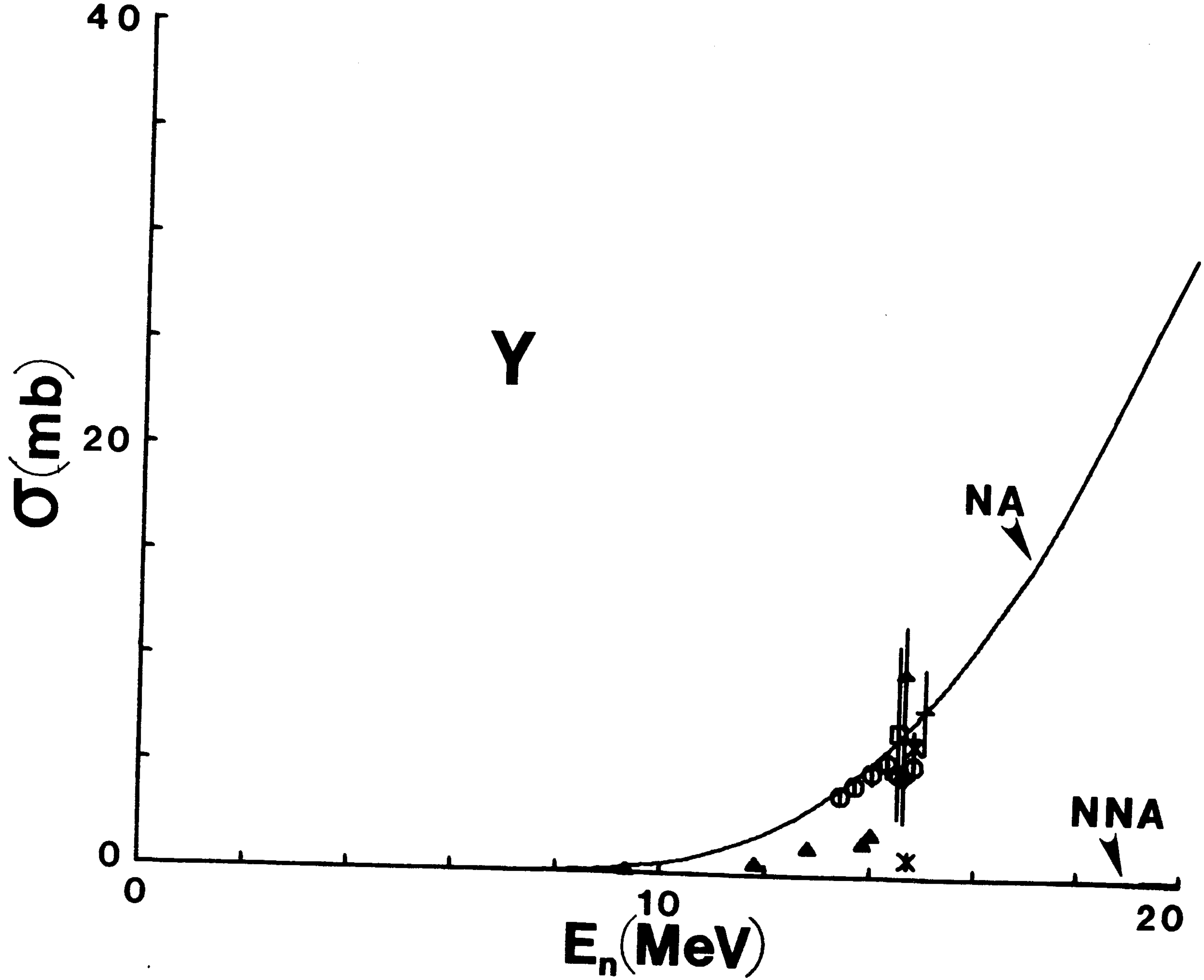


Fig. 10. (n,alpha) and (n;n',alpha) cross sections. Symbols indicate measured (n,alpha) values and the curves the two evaluated

(n;n',alpha) cross sections are negligibly small. The estimated uncertainties associated with these two evaluated components are large, 30% or more. The neutron-emission spectra resulting from the (n;n',alpha) reaction were assumed to be simple temperature distributions. This rather crude approximation is generally suitable in view of the very small size of the respective cross sections and the anticipated usage of this file. There is no comparable ENDF/B-V file.

IX-3. Minor (n,X) processes

The remaining (n,X) reactions are generally small and have relatively high-energy thresholds. They are included in the present evaluation for completeness, though they will have very little effect upon most neutronic applications. For unusual applications, where they may be of more concern, the reader is referred to special libraries (1).

The experimental knowledge of the (n,d) reaction is confined to the single 15 MeV direct-particle-detection result of Haight et al. (74). There is no active reaction product. The present evaluation uses calculations (24) to guide the energy-dependent shape and normalizes the calculated result to the measured value of ref. 74. The estimated evaluation uncertainties are large (30+%), but the respective cross sections are relatively small over much of the energy range of the evaluation, and that of most applied interest. The (n;n',d) threshold is at approximately 16 MeV. The cross section will not rise to significantly large values within the energy range of the present evaluation (upper limit 20 MeV), therefore the reaction was ignored in the evaluation.

There have been several measurements of the (n,t) reaction near 14 MeV (81,82). The results are not particularly consistent but they all are in the few micro-barn range. At 22 MeV the experimental results of ref. 83 suggest larger total tritium production cross sections (a few mb). These latter results are probably considerably enhanced by a relatively large contribution from the (n;n',t) process. The (n,t) reaction is qualitatively included in the evaluation for completeness, while the (n;n',t) reaction is ignored as the threshold is very high (approximately 18 MeV).

The (n,^{3}He) and (n;n',^{3}He) reactions appear, from systematics (83), to be very similar to the (n,t) and (n;n',t) processes and have similar thresholds. The (n,^{3}He) reaction is qualitatively included in the evaluation and the (n;n',^{3}He) process is ignored (threshold near 20 MeV).

X. Gamma-ray production processes

Gamma-ray production is dealt with in two parts: the first part is for the gamma-rays resulting from neutron radiative capture and the second is for the gamma-rays from all other gamma-producing reactions.

For the capture process, the spectral measurements of ref. 84 for thermal neutrons were used for incident neutrons of all energies. For the least incident-neutron energy a multiplicity was derived from the quotient of the Q-value of the reaction and the average energy of the measured photon spectrum. For greater neutron energies, conservation of energy was maintained by adjusting the multiplicity such that:

$$M(E_n) = M(E_0)*(E_n+Q)/Q.$$

Photon-production cross sections and spectra for photons resulting from all other reactions were obtained by calculation through a multi-step process. First, explicit energy distributions for the charged particles arising from all charged-particle producing reactions were calculated at appropriate incident neutron energies. Next, the average neutron, charged-particle and residual-nucleus energies were subtracted from the available (E_n+Q) energy of each reaction for an appropriate mesh of incident neutron energies. The resulting incident-neutron-energy-dependent available photon energies for each reaction and the reaction cross sections were combined using the R-parameter method of ref. 85 to obtain gamma-ray spectra and production cross sections.

XI. Integral tests

It was not possible to perform any integral tests on these evaluated data because there are not integral experiments against which calculated values may be compared. The closest to integral testing that was possible were the energy-conservation checks that are performed subsequent to obtaining the gamma-ray production cross sections and spectra. In that procedure the total energy available for photon production is checked against the energy produced by the calculated photon-production cross sections and spectra. Any discrepancies greater than 0.1 MeV and greater than 10% are noted. Had any been found, the photon-production cross section would have been adjusted to conserve energy within the criterion of acceptability. None were found, so the data were not changed.

XII. Outstanding problems

The energy-averaged neutron total cross sections are generally very well-known. However, the evaluation relies upon a single set of measurements at energies above approximately 15 MeV. That single experimental data set is probably reliable, but if there is an opportunity for total cross section measurements to 1% accuracy at energies above 15 MeV they should be made.

The elastic-scattering data base below 10 MeV is very good, and model extrapolations to 20 MeV are believed to be reasonably reliable. That is fortunate as the precise determination of the elastic cross section is important to the evaluation from the point of view of determination of the nonelastic cross section. Differential elastic-scattering cross sections should be determined at several (e.g., five) energies between 10-20 MeV to very good accuracy. Some preliminary data of this nature have been cited in the literature, but they are not available for use nor are they known to be of the requisite accuracy (e.g., permit determination of the angle-integrated elastic-scattering cross section to better than 5%). There is also some basic physical interest in this type of measurement, for the assessment of the fundamental properties of the optical model.

Discrete-inelastic-scattering cross sections are probably sufficiently well-known for applied purposes. There is only modest experimental knowledge of continuum-inelastic scattering below the (n,2n') threshold, and none above it. Careful neutron double-differential emission measurements are needed for incident energies of 5-20 MeV. This particular nucleus offers an unusual opportunity to study the continuum-inelastic-process over a wide energy range due to the exceptionally high threshold energy for the (n,2n') process. Generally, and in this case in particular, any information dealing with statistical level properties that would enhance the ability to calculate high-energy neutron emission is desirable. Improved knowledge of excited-level properties well above the contemporary approximately 3.2-MeV limit would make possible a better transition from discrete to continuum processes.

(n,2n') cross sections are well-known and probably do not warrant further attention in the foreseeable future. The corresponding emission spectra are a consideration, as noted above.

The present evaluation indicates large changes from the ENDF/B-V values for radiative-capture cross sections, and these are important in the assessment of fission-product effects. These changes are largely the result of new, and much lower, experimental values. Even with the latter new results, the data base is weak from a few keV to 500 keV, and new measurements to 5-10% accuracies would be very valuable.

(n,p) cross sections are not well defined. They are accessible with standard activation techniques, and results should be obtained to accuracies of approximately 10%. The (n;n'p) cross sections are large and very uncertain. Measurements are difficult due to the fact that the reaction product is stable. Measurements of the total hydrogen production below 14 MeV would be particularly useful in improving the evaluation and in testing the relevant calculational models.

The (n,alpha) cross section is not well-known and it is accessible through standard activation techniques. It should be determined to 10% accuracy. The (n;n',alpha) process is very poorly known but the cross sections are too small to warrant much attention.

The preceding suggestions are in the context of the present neutronic file. Other motivations may lead to alternate choices.

XIII. Summary comments

This report documents an evaluated neutronic file that should be very suitable for the assessment of the neutronic behavior of yttrium in a number of nuclear-energy applications. The relevance is largely at energies of less than 10 MeV, and the file gives primary attention to that area. The file should be suitable for qualitative predictions of the neutronic properties of integral systems characterized by energies well above 10 MeV. There are possible special-purpose applied interests (e.g., tritium production) where the user should augment the contents of this file with additional information (e.g., that of ref. 1). In a number of sensitive areas the present file is very different from that of ENDF/B-V. The differences are of a magnitude and character that may have a strong impact in some applications. The present file is reasonably supported by the newer and more accurate experimental information. Thus it is recommended that the present file replace the prior ENDF/B-V file in common applied usage as soon as possible.

Acknowledgments

The authors are indebted to a number of personnel in the Applied Physics Division, Argonne National Laboratory, for their support in various aspects of this work.

References

1. For example, M. Gardner and R. Howerton, Livermore Lab. Report, UCRL-50400, Vol-18 (1978).
2. A. Smith, P. Guenther and J. Whalen, Nucl. Phys. A415 1 (1984).
3. A. Smith, P. Guenther and R. Lawson, to be published (1986).
4. C. Budtz-Jörgensen, P. Guenther, A. Smith and J. Whalen, Argonne Lab. Report, ANL/NDM-79 (1982).
5. C. Budtz-Jörgensen, P. Guenther, J. Whalen, W. McMurray, M. Renan, I. van Heerden and A. Smith, Z. Phys. A319 47 (1984).
6. S. Mughabghab, M. Divadeenam and N. Holden, Neutron Cross Sections, Vol-1, Part-A, Academic Press, N.Y. (1981).
7. D. Cullen, Program RECENT(version 79-1), Livermore Lab. Report, UCRL-50400, Vol-17, Part-C (1979).
8. J. Whalen and J. Meadows, Argonne Lab. Report, ANL-7310 (1968), 0.1-0.68 MeV.
9. W. Poenitz and J. Whalen, Argonne Lab. Report, ANL/NDM-80 (1983), 0.047-20.0 MeV.
10. D. Foster and D. Glasgow, Phys. Rev. C3 576 (1971), 2.5-15.0 MeV.
11. J. Coon, Phys. Rev. 88 562 (1952), 14.0 MeV.
12. W. Good et al., Phys. Rev. 109 926 (1958), 0.01-0.018 MeV.
13. A. Carlson and H. Barschall, Phys. Rev. 158 1142 (1967), 4.5-7.0 MeV.
14. H. Newson et al., Phys. Rev. 105 1981 (1957), 0.01-0.07 MeV.
15. D. Kent et al., Phys. Rev. 125 331 (1962), 3.6 MeV.
16. D. Miller et al., Phys. Rev. 88 83 (1952), 0.5-3.2 MeV.
17. K. Seth, Phys. Lett. 16 306 (1965), 0.1-0.65 MeV.
18. E. Islam et al., Nucl. Phys. A209 1891 (1973), 1.0-2.0 MeV.
19. W. Poenitz, Brookhaven Lab. Report, BNL-NCS-51363 (1981).
20. F. Perey and W. Kinney, Oak Ridge Lab. Report, ORNL-4552 (1970).
21. E. Ramström, Nucl. Phys. A315 143 (1979).
22. J. Towle, Nucl. Phys. A131 561 (1969).
23. S. Shafroth et al., Phys. Rev. 129 704 (1963).
24. M. Blann, private communication (1985).
25. P. Guenther, private communication (1985).
26. D. Nethaway, Nucl. Phys. A190 635 (1972), activation.
27. S. Ghorgi et al., Nucl. Phys. A266 53 (1976), activation.
28. P. Eapen and G. Salaita, J. Inorg. and Nucl. Chem., 37 1121 (1975), activation.
29. B. Bayhurst et al., Phys. Rev. C12 451 (1975), activation.
30. H. Tewes et al., Livermore Lab. Report, UCRL-6028 (1960), activation.
31. O. Hudson and I. Morgan, Bull. Am. Phys. Soc. 6 506 (1961), activation.
32. R. Rieder and H. Muenzer, Oesterr. Akad. Wiss., Math-Naturw., 175 53 (1966), activation.
33. H. Vonach and H. Muenzer, Oesterr. Akad. Wiss., Math-Naturw., 96 (1959), activation.
34. D. Vallis, Aldermaston Report, AWRE-0-76/66 (1966), activation.
35. S. Qaim and G. Stoecklin, Euratom Report, EUR-5182E (1974), activation.
36. W. Mannhart and H. Vonach, Z. Phys. A272 279 (1975), activation.

37. M. Borman et al., Z. Phys. A277 203 (1979), activation.
38. K. Kayashima et al., NEANDC Report, NEANDC(J)-61U (1979), activation.
39. B. Granger and M. Longueve, NEANDC Report, NEANDC(E)-49L (1963), activation.
40. A. Abboud et al., Acta. Physica Polonia B2 527 (1971), activation.
41. J. Laurec et al., CEA Report, CEA-R-5109 (1981), activation.
42. J. Csikai and G. Peto, Acta. Phys. Acad. Sci. Hungary 23 87 (1967), activation.
43. J. Araminiovicz and J. Dresler, Inst. Badan Jadrowych Report, INR 1494 14 (1973), activation.
44. P. Raics et al., Atomki Kozlemenyek 23 45 (1981), activation.
45. Huan Jian-Zhou et al., Chinese J. Nucl. Phys. 2 213 (1980), activation.
46. J. Frehaut et al., Brookhaven Lab. Report, BNL-399 (1980), direct detection.
47. D. Mathur and L. Pain, Aldermaston Report, AWRE-O-47/69 (1969), direct detection.
48. D. Mathur et al., Aldermaston Report, AWRE-O-72/72 (1972), direct detection.
49. L. Veeser et al., Phys. Rev. C16 1792 (1977), direct detection.
50. C. Philis, CEA Report, CEA-R-4636 (1975).
51. W. Poenitz, Argonne Report, ANL-83-4 (1983).
52. A. Bostrom et al., Texas Nucl. Report, WADC-TN-59 107 (1959).
53. J. Gibbons et al., Phys. Rev. 122 182 (1961).
54. R. Macklin and J. Gibbons, Nucl. Phys. 43 353 (1963).
55. R. Both et al., Phys. Rev. 112 226 (1958).
56. B. Diven et al., Phys. Rev. 120 556 (1960).
57. R. Macklin and J. Gibbons, Phys. Rev. 159 1007 (1967).
58. B. Rustad et al., AEC Report, NYO-72-28 92 (1966).
59. F. Rigaud et al., Nucl. Phys. A154 243 (1970).
60. T. Ryves and D. Perkins, J. Nucl. Energy 25 129 (1971).
61. G. Peto, J. Nucl. Energy 21 797 (1967).
62. J. Csikai et al., Nucl. Phys. A95 229 (1967).
63. W. Budnar et al., IAEA Report, INDC(YUG) 6 (1979).
64. V. Tolstikov et al., Atom Energy 21 6-506 (1966).
65. A. Bergman et al., Jaderno-Fizicheskie Issledovanija 3 9 (1966).
66. J. Boldeman et al., Nucl. Sci. and Eng. 64 744 (1977).
67. I. Bergqvist et al., Nucl. Phys. A295 256 (1978).
68. S. Joly et al., Bull. Am. Phys. Soc. 24 87 (1979), also National Bureau of Standards Pub. NBS-594 (1979).
69. P. Moldauer, private communication (1983).
70. B. Bayhurst and R. Prestwood, J. Inorg. Nucl. Chem. 23 173 (1961).
71. H. Tewes et al., Lawrence Livermore Lab. Report, UCRL-6028-T (1960).
72. J. Csikai and L. Nagy, Nucl. Phys. A91 222 (1967).
73. V. Levkovsky et al., Jadernaja Fizika 8 7 (1968).
74. R. Haight et al., Phys. Rev. C23 700 (1981).
75. E. Arthur, Los Alamos Lab. Report, LA-7789-MS (1979).
76. D. Wilmore, Harwell Report AERE-R 11515 (December, 1984).

77. E. Paul and R. Clarke, Can. J. Phys. 31 267 (1953).
78. E. Bramlitt and R. Fink, Phys. Rev. 131 2649 (1963).
79. K. Kayashima et al., NEANDC Report, NEANDC(J)-61U 94 (1979).
80. P. Strohal et al., Nucl. Phys. 30 49 (1962).
81. S. Qaim et al., J. Radioanalytical Chem. 21 295 (1974).
82. M. Diksic et al., J. Inorg. and Nucl. Chem. 36 477 (1974).
83. S. Qaim and R. Wolfle, Nucl. Phys. A295 150 (1978).
84. V. Orphan, N. Rasmussen and T. Harper "Line and Continuum Gamma-Ray Yields from Thermal Neutron Capture in 75 Elements", General Atomics Report, GA-10248 (1970).
85. S. Perkins, R. Haight and R. Howerton, Nucl. Sci. and Eng. 57, 1-11 (1975).